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The infrared imaging spectrograph (IRIS) for TMT: design of image slicer

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ABSTRACT

The InfraRed Imaging Spectrograph (IRIS) is one of three first light science instruments for the Thirty Meter Telescope (TMT). It will provide dedicated function of imaging and integral field spectroscopic observations in parallel with the assistance of a Narrow Field InfraRed Adaptive Optics System (NFIRAOS). The IRIS imager delivers celestial light to a dual-channel Integral Field Spectrograph (IFS) through a pair of pick-off mirrors in the central field. The IFS creates multi-functional ability to explore the universe in IR (0.84 – 2.4um) with moderate spectral resolution of R=4,000/8,000 and four spaxel scales of 4, 9, 25, 50 milli-arc-seconds (mas). An image slicer serves one of the two spectral channels as its Integral Field Unit (IFU) in two coarse spaxel scales of 25 and 50mas over the continuous science fields of 2.2x1.125 arc-seconds (arcsec) and 4.4x2.25 arcsec respectively. It splits the field to 88 unit systems, and then re-images at two parallel slits in order to take full advantage of the detector (4Kx4K @ 15um). This paper describes a novel all-reflective design of image slicer, which uses a new 'brick stage' layout to stagger the adjacent mirrors and deliver image quality close to diffraction limit. The quasi-telecentric optical design gives more friendly interfaces with pre-optics and spectrograph than the conceptual design. Here, more technical issues are discussed to guide the further study on optical performance and fabrication feasibility.

Keywords: Thirty Meter Telescope, Infrared Imaging Spectrograph, Integral Field Unit, Image Slicer

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1. INTRODUCTION

In the TMT first-light instrument plan, the InfraRed Imaging Spectrograph (IRIS) will provide dedicated function of imaging and integral field spectroscopic observations in parallel with the assistance of a Narrow Field InfraRed Adaptive Optics System (NFIRAOS). The imager delivers celestial light to a hybrid Integral Field Spectrograph (IFS) through a pair of pick-off mirrors in front of the imager detector, see Figure 1. The IFS creates multi-functional ability to explore the universe in IR (0.84 – 2.4um) with moderate spectral resolution and four spaxel scales, see Table 1 [1] [2].

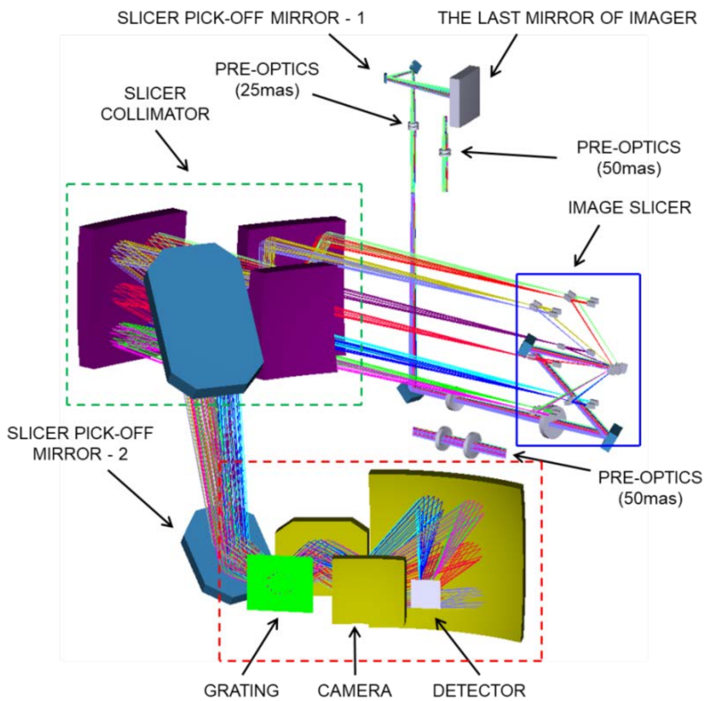

Figure 1. Preliminary optical model for Slicer IFS

(The optics from the pick-off mirror after imager to the detector; the model in blue solid cell is part of image slicer; the model in green dash cell is the Slicer collimator; the model in red dash cell is the common camera.)

Table 1. Capabilities of dual channel IFS

Capability mode (Spaxels)	Spatial sampling (mas)	FoV (arcsec)	Resolution (λ/Δλ)	Min/Max wavelength (um)	Bandpass
Slicer IFS	50	4.4x2.25	4,000	0.84-2.4	20%, 10%
(88x45)	25	2.2x1.125	10,000	0.84-2.4	20%, 10%
Slicer IFS	50	2.2x2.25	4,000-10,000	0.84-2.4	20%, 10%, H+K
(44x45)	25	1.1x1.125		0.84-2.4	20%, 10%, H+K
Lenslet IFS	9	1.01x1.15	4,000	0.84-2.4	5%
(112x128)	4	0.45x0.51	10,000	0.84-2.4	5%

Lenslet IFS	9	0.144x1.15	4,000-10,000	0.84-2.4	20%, H+K
(16x128)	4	0.064x0.51		0.84-2.4	20%, H+K

The hybrid IFS are separated to two spaxel modes by the types of Integral Field Unit (IFU) in order to make balance among spaxel scale, integral field, bandpass and image quality. An image slicer serves the coarse spaxel modes of 25mas and 50mas over the continuous science fields of 2.2x1.125 arc-seconds (arcsec) and 4.4x2.25 arcsec respectively.

It splits the field to 88 unit systems, and then re-images at two parallel long slits in order to take full advantage of the detector (4K x 4K pixels @ 15um). On the detector, two rows of spectrum are evenly distributed along the direction perpendicular to dispersion, see Figure 2. Every spectrum occupies 45 spaxels with equivalent to 90 pixels at sampling rate of 2x2 pixels, and it theoretically retains 3 pixels between the adjacent spectrum.

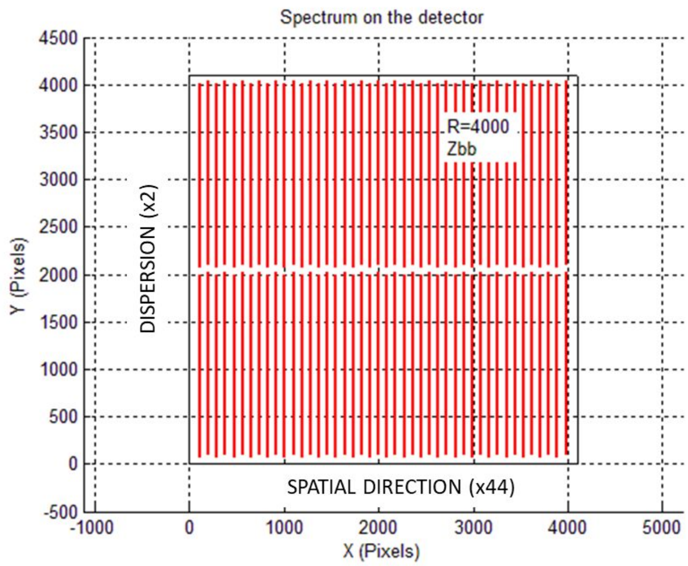

Figure 2. Spectrum layout on the detector in the mode of 88x45 spaxels

Refer to some existing image slicer IFUs, see Table 2, it proves that the 3-mirror design is more feasible for the TMT-IRIS than the others. Firstly, every long slit accommodates 44 slitlets so that the fold angle of optical path increases up to 30 degree or bigger. It requires stronger capability to correct the corresponding off-axis aberration. Secondly, its wavelength range (0.84-2.4um) covers quite wide photometric bands (Z, Y, J, H, K). It requires all-reflective optics to avoid chromatic aberration. Thirdly, an effective image mask at real slit plane is quite important for the IFS to restrict stray light in IR.

Table 2. Capabilities of some Slicer IFS in the world

IFS	Telescope	Spatial resolution (arcsec)	FOV (arcsec)	Wavelength (um)	Number of slicers	Optics
GNIRS[3]	Gemini S (8.1m)	0.05/0.12/0.15	3.2×4.8	0.9-2.5	21	3-mirror

KCWI[4]	Keck (10m)	0.35 0.7 1.4	8.4×20 16.8×20 33.6×20	0.35-1.05	24	2-mirror
NIFS[5]	Gemini N (8.1m)	0.04×0.1	3×3	0.95-2.4	29	3-mirror
SPIFFI[6]	VLT (8.2m)	0.025 0.1 0.25	8×8, 3×3, 0.8×0.8	1.1-2.45	32	2-mirror
SWIFT[7]	Hale (5.1m)	0.08 0.16 0.235	10.3×20.9, 7.0×14.2, 3.5×7.1	0.65-1	44	3-catadioptrics
MUSE[8]	VLT (8.2m)	0.2 (0.025)	60×60 (7.5×7.5)	0.48-0.93	1152 (24x4x12)	2-mirror (Modularization)
NIRSpec[9]	JWST (6.5m)	0.1	3x3	0.7-5.0	30	3-mirror

At the Conceptual Design Phase (CoDP), the image slicer adopts a kind of 3-mirror design, which is composed of Slicer Stack (SS), Pupil Mirror Array (PMA) and Slit Mirror Array (SMA), see Figure 3. Therein, flat thin slicer reflects sliced field to every independent unit system; pupil mirror and slit mirror are powered for jointly reimaging and pupil projection. Each mirror in the SS is 0.4mm x 18mm, each mirror in the PMA is 6.75mm x 6.75mm, and each mirror in the SMA is 3mm x 6mm. Every slitlet is only 0.064mm x 2.88mm at the output focal ratio of F/8.8. The CoD has to use a kind of 'brick stage' layout to stagger the adjacent mirrors. It results in every long slit comprises two rows of slitlets (2x22), which gets double spacing along the spatial direction.

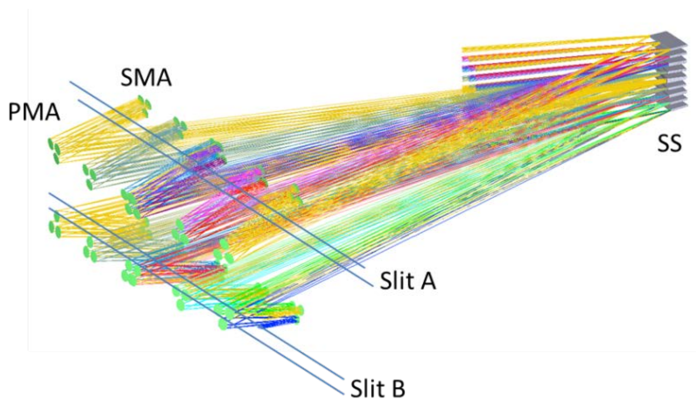

Figure 3. Conceptual design of IRIS image slicer

At the Preliminary Design Phase (PDP), the image slicer is redesigned to (1) Improve the image quality at the detector that was limited at the CoD phase by defocus in the IFU itself. (2) Reduce the cost by using a spherical slicer stack and increasing the size of pupil and slit mirrors (PMA/SMA) to sizes that were fabricated easily. The detailed design is discussed at the following sections, respectively Section 2 and 3 describes the optical design and its optical performance;

Section 4 discusses some accessibility to fabrication and the related study on prototype; Section 5 summarizes the preliminary design and feasible study at the ongoing phase.

2. OPTICAL DESIGN

Through further study on typical 3-mirror design, it's indicated that big fold angle on spherical mirror is the primary reason to degrade image quality, especially spherical pupil mirror, see Figure 4. Flat pupil mirrors used in some 2-mirror designs don't cause this serious degradation, for example, Keck II – KCWI [4] and VLT – SPIFFI [6]. And the design of Hale – SWIFT [7] and VLT – MUSE [8] also verifies that it's feasible to compensate the imaging function deletion of flat pupil mirror by locating slit mirror at a specific position.

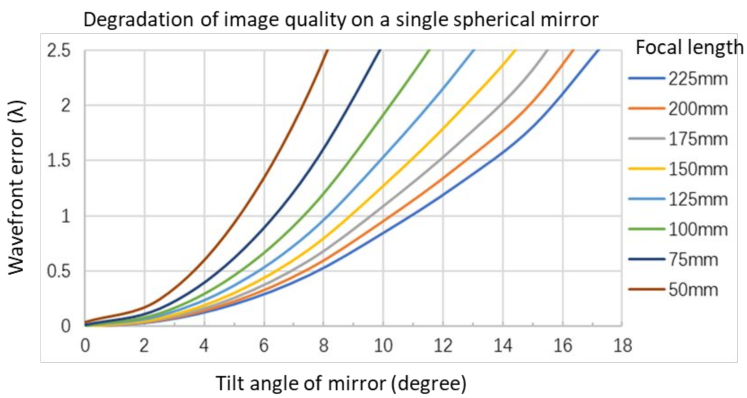

Figure 4. Conceptual design of IRIS image slicer

For the conventional slicer stack, thin flat mirror must be independently polished to get the required pointing direction. It's not the optimal way to build a stack of 88 slicers. The off-axis portion on a spherical surface enables to provide different fold angle of chief ray by its decenter (dx, dy), when the surface has a defined central axis. It's a WINLIGHT Optics/CNRS patent technology to simultaneously polish a few slicers staggered on a common spherical surface [10].

Combined with these inspirations, the preliminary design makes the following adjustment, and Table 3 lists the related first order parameters.

1. New 3-mirror design improves image quality by using flat pupil mirrors.
2. Spherical slicer is used to reduce its manufacture cost and period.
3. Entrance and exit pupils are located at infinite to match the using of spherical slicer and provide more friendly access to pre-optics and collimator of spectrograph.
4. Size of the PMA/SMA mirrors is increased to 10mm for easing manufacture. This change resulted in a factor of 2 increase in the physical size of the long slit.
5. Output focal ratio and speed of collimator are reduced to F/15.4 for matching the amplified long slit.

Table 3. First order parameters of image slicer

Design phase	CoDP	PDP

Spaxel mode	25mas	50mas	25mas	50mas
Wavelength range (um)	0.84-2.4	0.84-2.4	0.84-2.4	0.84-2.4
FOV (arcsec)	2.2x1.125	4.4x2.25	2.2x1.125	4.4x2.25
Input F/#	F/110	F/55	F/110	F/55
FOV (mm)	35.2x18	35.2x18	35.2x18	35.2x18
Number of slicers	88	88	88	88
Size of slicer (mm)	0.4x18	0.4x18	0.4x18	0.4x18
Size of pupil mirror (mm)	6.75x6.75	6.75x6.75	4.7x10.416	4.7x10.416
Size of slit mirror (mm)	3x6	3x6	5.4x10.416	5.4x10.416
Output F/#	F/17.6	F/8.8	F/30.8	F/15.4
Size of slitlet (mm)	0.064x2.88	0.064x2.88	0.112x5.04	0.112x5.04
Location of entrance/exit pupil	+328/-1311mm	+328/-1311mm	Infinity/Infinity	Infinity/Infinity

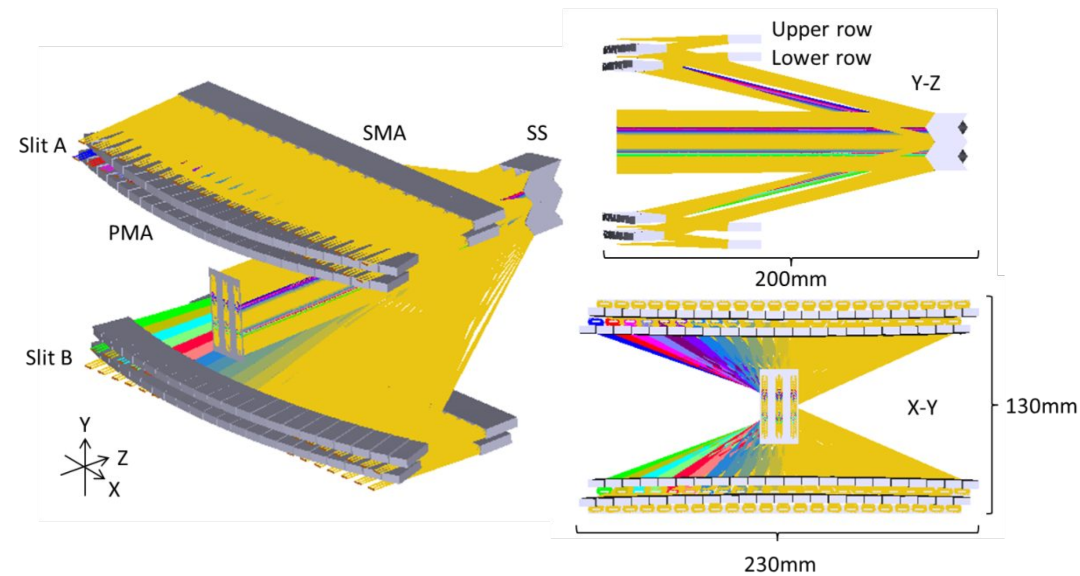

Figure 5. Optical model of preliminary design

In the preliminary optical model, the slicer stack separates the whole integral field to two symmetric modules, each of which generates a long slit (A/B); mirrors of the PMA are distributed along the arc shape in X-Z plane, and staggered like 'brick stage' in Y-Z plane; mirrors of the SMA locates at two corresponding straight rows, see Figure 5.

A new 'brick stage' layout is designed to reduce the difference in image quality among the unit systems at upper and lower rows. Output beam from the lower row of SMA pass through the interval between the upper and lower rows of PMA.

Figure 6 shows image layout at slit plane. The central distance between two long slits (A/B) is 114.7mm in Y dimension, with corresponding to half of CCD chip. In each slit, the spacing between two rows of slitlets is 10.7mm in Y dimension, and the slitlet spacing is 10.416mm in X dimension, with corresponding to 93 pixels on the detector, including 3 pixels gap. Over the whole slit plane, the image geometry meets the theoretical values very well with tiny coordinate error of less than 5um.

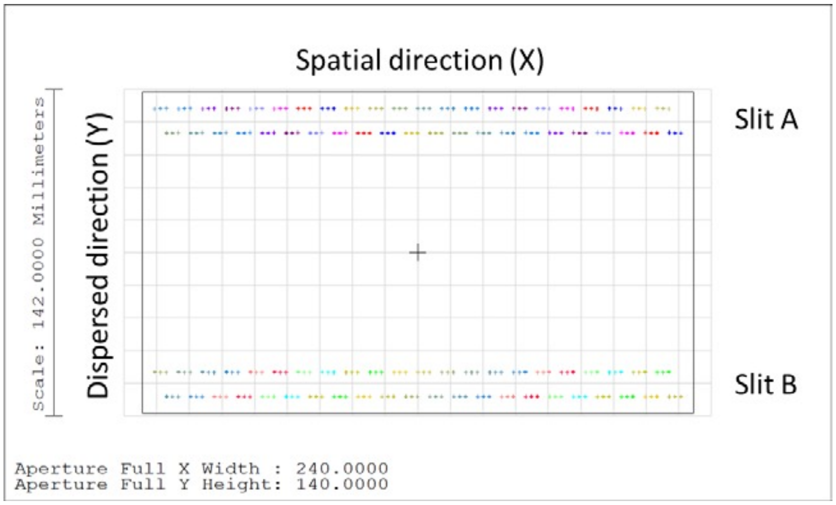

Figure 6. Image layout at slit plane

3. OPTICAL PERFORMANCE

For image slicer IFU, the consistence of optical performance among all unit systems is regarded as one of the most important criterion to evaluate the design. Figure 7 shows the deviation from the nominal output focal ratio is less than 3% in maximum, and also illustrates that it is a little difference of less than 5% between upper and lower rows. Figure 8 shows the angle distribution between the incident ray and the normal of slit plane. It verifies that difference of fold angle causes the phenomena of worse performance in upper row and non-symmetry in the same row, but also indicates the design is capable of providing friendly accessibility to telecentric collimator because of small angular error.

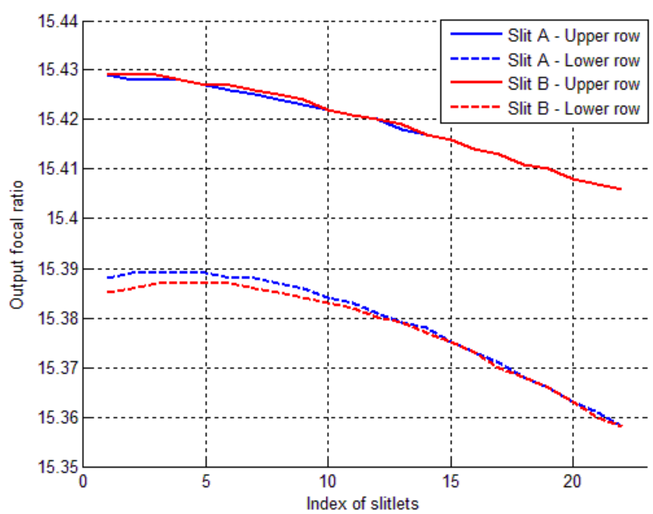

Figure 7. Distribution of output focal ratio

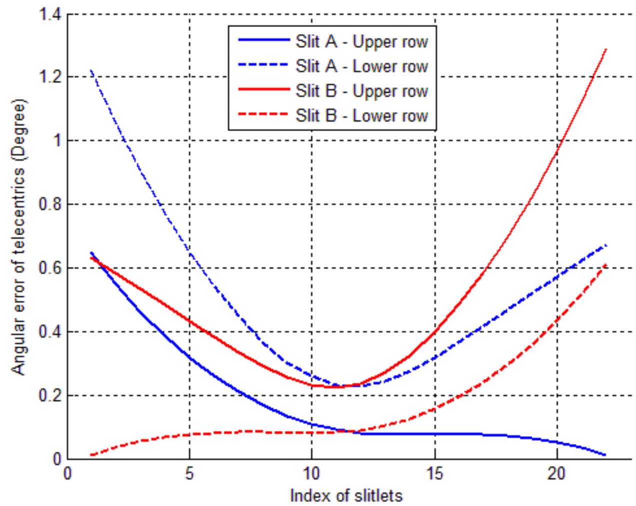

Figure 8. Distribution of telecentric angular error

Benefited from flat pupil mirror, the preliminary design gets geometric image quality close to diffraction limit identically among unit systems. It is only limited difference between the unit systems at edge and center, see Figure 9.

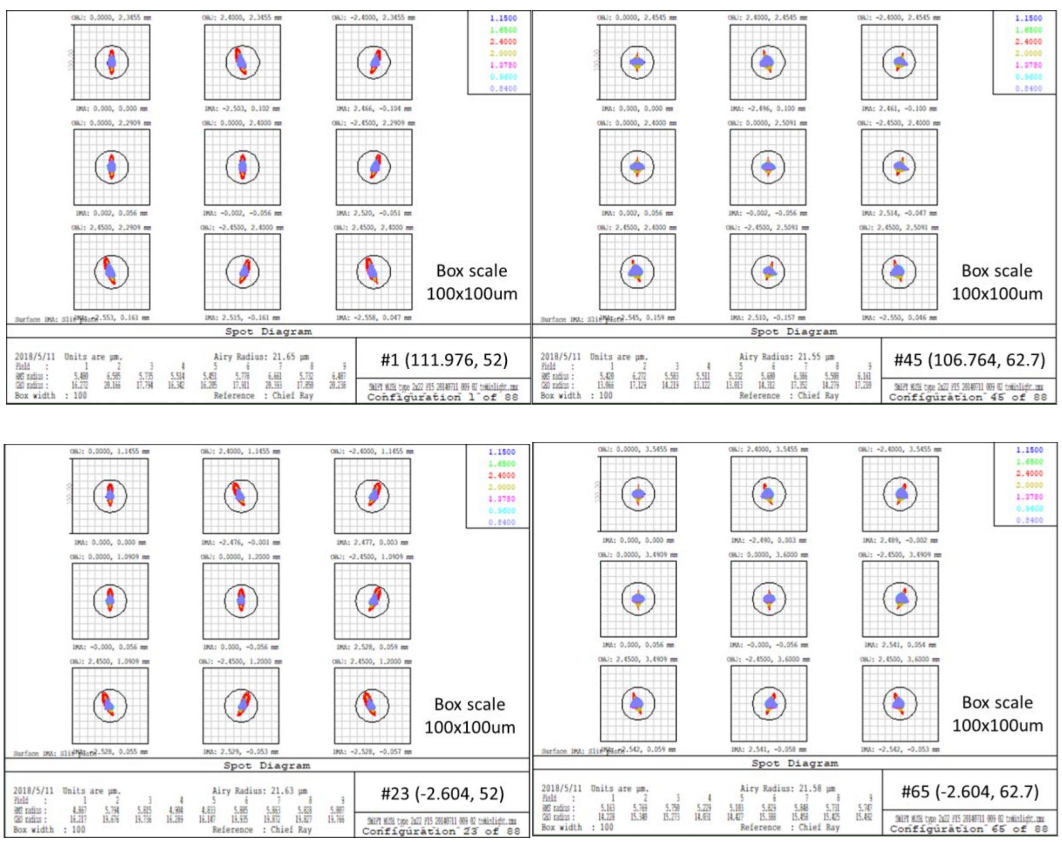

Figure 9. Spot diagram in part of unit systems

At the aspect of telecentric design, it doesn't only require that the optical axis of every unit system is parallel to the systematic optical axis, but also need checking the telecentricity in a single unit system. A single mirror can't achieve the latter requirement very well due to self-limitation of optics. It results in the common exit pupil at infinite is diffused by the field (1.125/2.25arcsec) along X dimension. Figure 10 evaluates the common exit pupil with a paraxial telecentric lenses instead of the collimator. The enveloped circle of ϕ110mm requires larger grating area to cover the whole light.

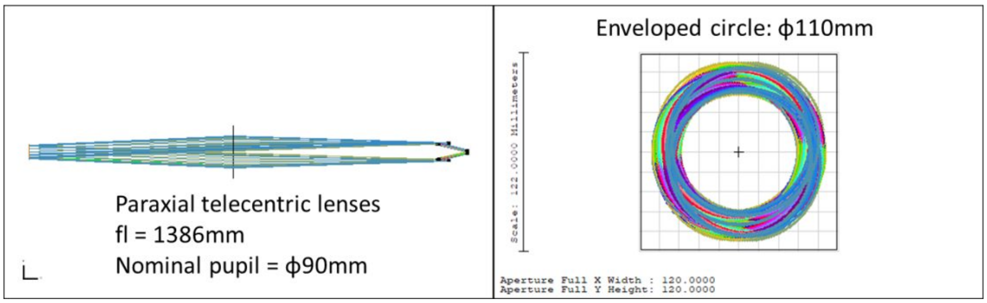

Figure 10. Common exit pupil

At the aspect of throughput estimation, it contains image quality, reflective coating and vignetting. There's negligible vignetting on the mirrors of PMA and SMA, see Figure 11 (a) and (b). Nevertheless, the staircase-like arrangement on SS obstructs some fields at the very edge of a slicer by the overhanging section of neighboring slicer, see the red zones in Figure 11 (c). Figure 11 (d) shows the simulated illumination on the SS, and the vignetting is small.

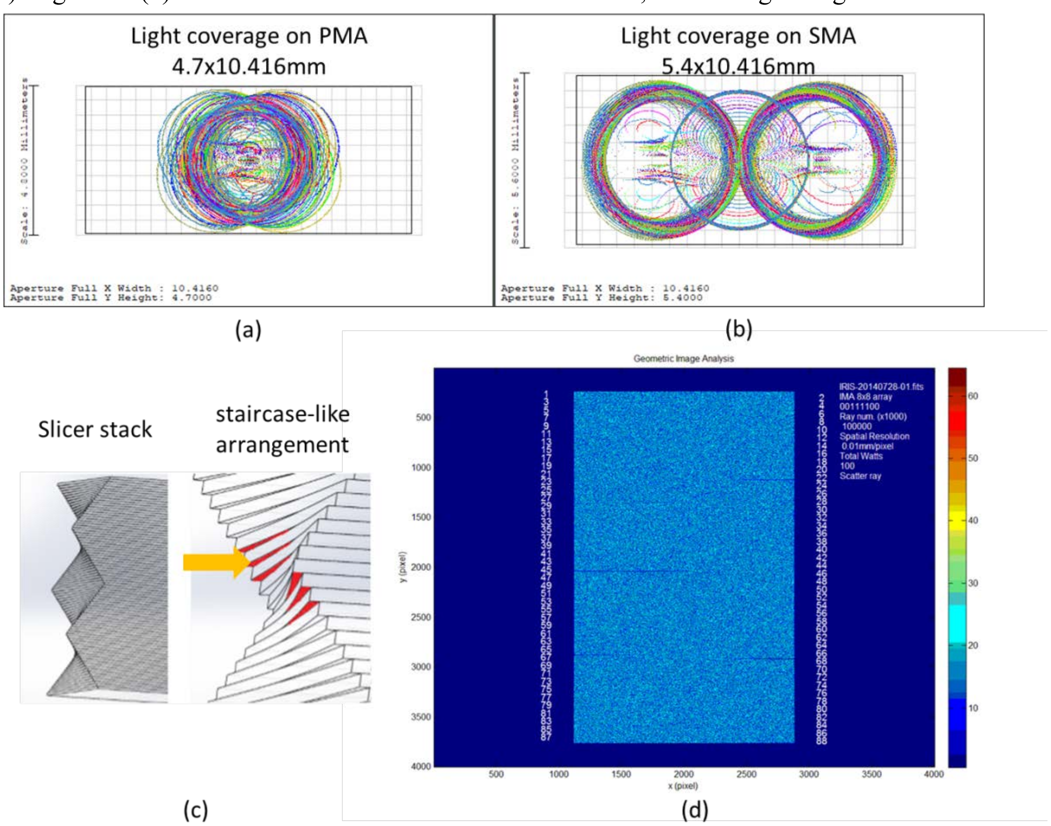

Figure 11. Vignetting analysis on different mirrors

It's unavoidable for the image slicer IFU to restrict stray light, especially in IR band. The optical model in Figure 5 is an open stereoscopic system, which must restrict stray light by using baffle structure and image mask. It's evidenced that most of stray light can be compressed by baffle structure, see Figure 12, and portion of stray light near the slitlets can be blocked by an image mask, but the residual stray light mixed with images is the most harmful factor. It is feasibly restricted by the follow-up spectrograph and data reduction.

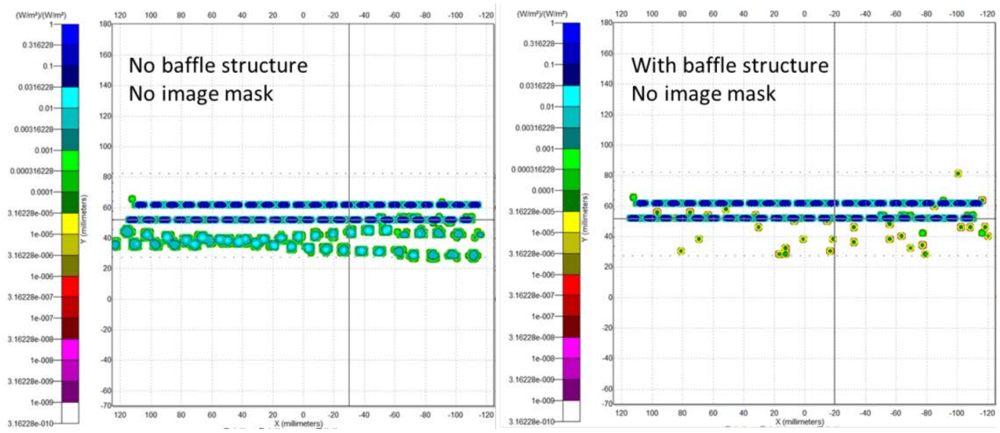

Figure 12. Simulation for restricting stray light

4. ACCESSIBILITY TO FABRICATION

The image slicer IFU is baselined as an all Zerodur glass assembly. This approach is readily cryogenic and offers excellent surface roughness performance required for the bluest wavelengths. Under this premise, more related consideration is integrated into the preliminary design.

1. SLICER STACK

Application of spherical slicers is based on the technology to simultaneously polish serval mirrors. According to the investigation [10] [11], the sequential slicers are 'staircase-like' staggered on a spherical substrate, see Figure 13. After polishing, the slicers are combined along the dispersed direction (Y) to be a stack by optical cement.

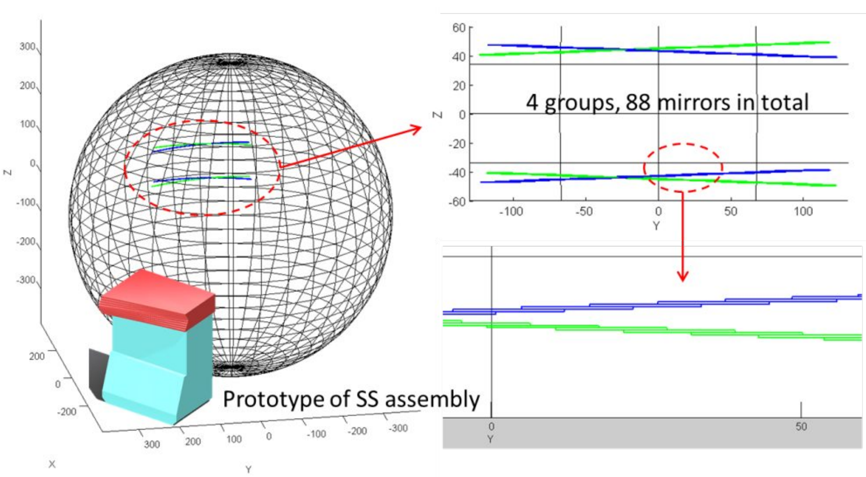

Figure 13. Coordinates of slicers on a spherical surface

2. PUPIL MIRROR ARRAY

Every row of PMA is designed as the assembly of 22 different prisms. The adjacent mirrors are glued together by the lateral side, and the back surface is the datum to glue with the base, see Figure 14 (a). Each mirror has to be polished one by one as same as the slicer at the CoDP, but its dimension increases up to 4.7mmx10mm so that it's more convenient to manufacture in the normal way.

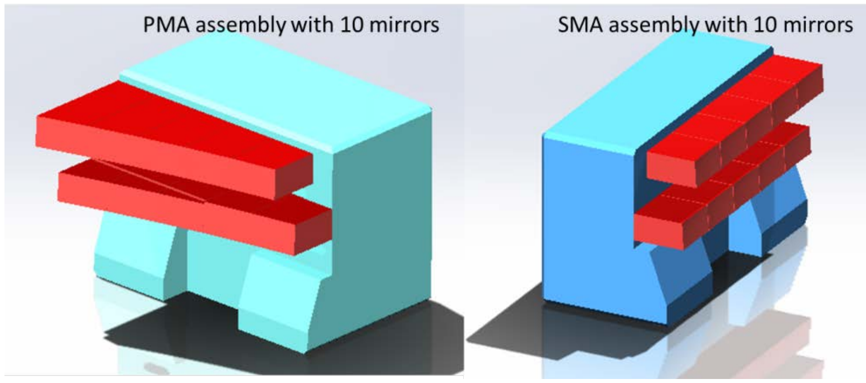

Figure 14. Prototype of PMA and SMA assembles

3. SLIT MIRROR ARRAY

The SMA assembly is integrated by using the lateral and back surfaces of each mirror as same as the PMA assembly, see Figure 14 (b), however, the mirror is polished in different process from the PMA and the SS. For the preliminary design, every mirror of the SMA has only decenter in Y dimension. Its fabrication is generalized as three steps, see Figure 15: (a) Polish cylindrical substrates with the same spherical surface, (b) Grind out the required decenter surface and test in self-collimation method, (c) Grind out the external dimension based on the decenter surface.

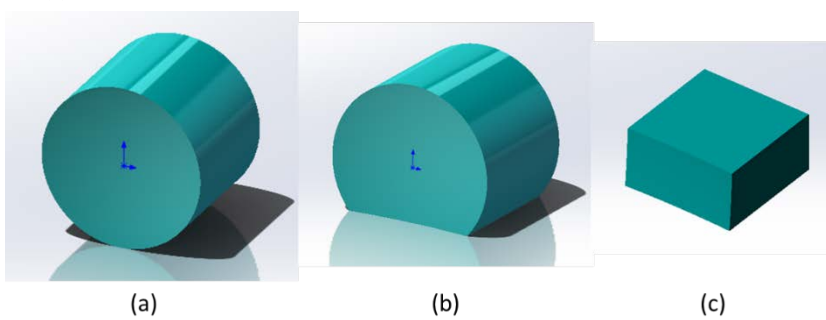

Figure 15. Feasible manufacturing scheme for the SMA

To further study on image slicer IFU, a prototype with 10 unit systems at the edge is designed to investigate the feasible mechanism and metrology, see Figure 16. Its mechanics takes reference of the VLT-MUSE's 'plug and play' scheme [12]. Pointing and positioning precision of each mirror are defined by a reference optical part on its base. And the mechanical parts are tested and modified to compensate the residual geometric error of optical assembly by the CMM (Coordinate Measuring Machine) and high precision machining center. Finally, three optical assemblies are fixed on the mechanical structure by the clamps.

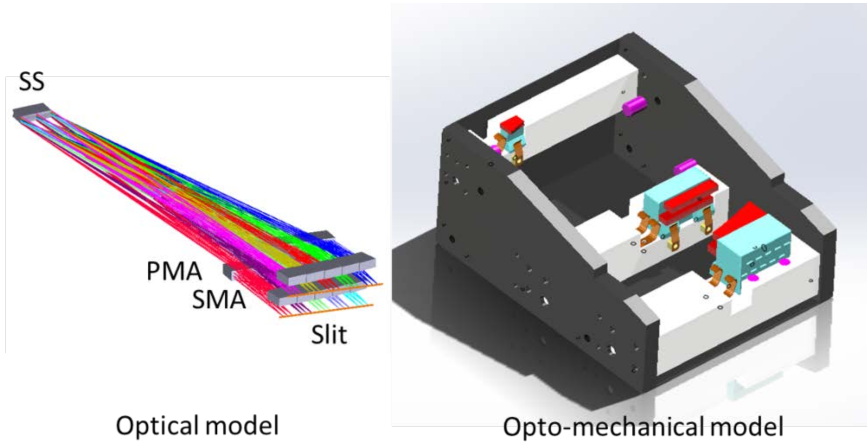

Figure 16. Opto-mechanical model of prototype

5. SUMMARY

The optical design for the IRIS image slicer IFU passed the Preliminary Design Review (PDR-1) in November of 2016. It fully combines the feature of 2-mirror design and 3-mirror design to optimize image quality and ease manufacture. As a result of this design, it achieves these primary goals through further evaluation at all aspects, including performance consistence, image geometry, image quality, vignetting, stray light and fabrication accessibility. Image slicer IFU is a special optical system relies on technology of optical process very much. The optical part has to carefully separate its physical parameters for two procedures in manufacture and integration, because they are so closely related for the image slicer IFU. And it's another of the most important factors to reduce its technical risk that studies on the optimal testing method and develops the related testing bench.

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REFERENCES

[1] Anna M. Moore, et al., “The Infrared Imaging Spectrograph (IRIS) for TMT: instrument overview,” Proc. SPIE 9147, 914724 (2014).

[2] James E. Larkin, et al., “The Infrared Imaging Spectrograph (IRIS) for TMT: instrument overview,” Proc. SPIE 9908, 99081W (2016).

[3] J. R. Allington-Smith, et al., “New techniques for integral field spectroscopy – I. Design, construction and testing of the GNIRS IFU,” Mon. Not. R. Astron. Soc. Papers 371, 380-394 (2006).

[4] Chris Martin, et al., “The Keck Cosmic Web Imager,” Proc. SPIE 7735, 77350M (2010).

[5] John Hart, et al., “NIFS concentric integral field unit,” Proc. SPIE 4841, 319-329 (2003).

[6] Matthias Tecza, et al., “The SPIFFI image slicer: Revival of image slicing with plane mirrors,” Proc. SPIE 4008, 1344-1350 (2000).

[7] Matthias Tecza, et al., “SWIFT: An adaptive optics assisted I/z band integral field spectrograph,” New Astronomy Reviews 49, 10-12 (2006).

[8] Johan Kosmalski, et al., “Optical Design of the VLT/MUSE instrument,” Proc. SPIE 8167, 816716 (2011).

[9] David J. Purll, et al., “The integral field unit for the james webb space telescope's near-infrared spectrograph,” Proc. ICSO2010 10565, 105650J (2010).

[10] S. Vives, et al., “New technological developments in Integral Field Spectroscopy,” Proc. SPIE 7018, 701897 (2008).

[11] Florence Laurent, et al., “MUSE Image Slicer: Test results on largest slicer ever manufactured,” Proc. SPIE 7018, 70180J (2008).

[12] Florence Laurent, et al., “MUSE Integral Field Unit: Test results on the first out of 24,” Proc. SPIE 7739, 7739M (2010).